Optimization of COVID-19 face mask waste fibers and silica fume as a balanced mechanical ameliorator of fat clay using response surface methodology

Zia ur Rehman¹ · Usama Khalid²

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Abstract

The balanced amelioration of mechanical characteristics of fat clay with an additive refers to the attainment of high strength without compromising ductility, which is unattainable by solitary usage of a cementing additive. For this purpose, an amalgamated binary admixture (ABA) is proposed by assimilating shredded face mask (FM) waste, which is posing serious environmental concerns these days, with a cementitious waste material, i.e., silica fume (SF). However, for such ABA, the optimization of mix design is desirable because an excessive amount of one component could disturb the required balance. To address this issue, response surface methodology (RSM) is used in the current study, which is a strong technique used during the process of production to develop, improve, and optimize product inputs. Several experiments are designed and conducted to evaluate mechanical responses, i.e., unconfined compressive strength (q_u), brittleness index (I_B), deformability index (I_D), and California bearing ratio (CBR) value, of treated fat clay by varying mix designs of ABA. Based on the test results, mathematical models are developed which are found to be statistically valid to predict the subjected responses using SF and FM as inputs. Afterward, an optimized mix design is determined by integrating developed models with a desirability function model and setting maximization of strength and ductility as the optimization goals. An ABA having 7.9% SF and 1.2% FM is observed to provide the highest strength and ductility for multiple applications, i.e., road and buildings, with desirability factor close to unity; responses of which are also validated by performing tests. Furthermore, analysis of cleaning aspect shows that the use of optimized ABA in place of cement for subgrade improvement of 1 km two-lane road could avoid CO₂ emission of around 79,032 kg of C, save 42,720 kWh and 1174.8 GJ of electrical and thermal energy, respectively, and clean 43 Mg of FM waste; however, astute protocols of COVID-19 FM waste handling and disinfection are needed to be established and followed.

Keywords COVID-19 face mask waste · Waste and pollution reduction · Ductility · Mechanical properties · Response surface methodology

Nomenclatures

3D Three-dimensional
A Represent the SF in Eqs. (8)–(11)

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✉ Zia ur Rehman
ziaur.rehman@uettaxila.edu.pk; engr.zrehman@gmail.com
Usama Khalid
engr.usamakhalid@yahoo.co.uk

¹ Department of Civil Engineering, University of Engineering and Technology (UET), Taxila 47080, Pakistan

² National Institute of Transportation (NIT), National University of Sciences and Technology (NUST), Risalpur 23200, Pakistan

ABA Amalgamated binary admixture
ANOVA Analysis of variance
ASTM American Society for Testing and Materials
 B Represent the FM in Eqs. (8)–(11)
CBR California bearing ratio
 D Global desirability
 I_B Brittleness index
 I_D Deformability index
FCCCD Face-centered central composite design
FM Face mask
 n Number of observations
 p Intercept of observations
PF Polypropylene fiber
PRESS Prediction error sum of squares
 q_u Unconfined compressive strength

q_r	Residual compressive strength
R^2	Coefficient of determination
RSM	Response surface methodology
SSM	Mean sum of squares
SSR	Residual sum of squares
SST	Total sum of square
USCS	Unified soil classification system
SF	Silica fume
w_{opt}	Optimum moisture content
ε_a	Axial strain
ε_f	Strain at failure
γ_{dmax}	Maximum dry unit weight
$\hat{Y}$	Predicted response value
σ^2	Mean square of residual
Max_i	Maximization value
Min_i	Minimization value
T_i	Target value

Introduction

Conservation of natural resources and multidisciplinary utilization of waste by-products as the substitute material under the concept of the circular economy has gained substantial attention in the last few decades. This approach is necessary for promoting productive environmental management, sustainable development, and economic growth. Recently, after getting hit by the COVID-19 pandemic, the realization of a clean ecosystem and need for the multidisciplinary proposals for environmental management is higher than ever, since the environmentalists have warned that the continuous COVID-19 pandemic could spur the ongoing environmental issues (Boroujeni et al. 2021; Van-Fan et al. 2021). Among different environment-related issues caused by this pandemic, the impact of COVID-19-related waste generation is of utmost concern (Sharma et al. 2020). Personal protective equipment (PPE)-related wastes like rubber gloves, face masks (FMs), and hand sanitary bottles lying on streets and floating on and below the water bodies have become a common observation of these days due to their extensive usage, as reported in various literature (Das et al. 2020; Dharmaraj et al. 2021), glimpsing the scale of this waste problem. As a pandemic control measure supported by various studies (Feng et al. 2020; Matuschek et al. 2020; Worby and Chang 2020), the World Health Organization (WHO) has introduced guidelines for the public to wear a surgical FM as a protective measure. As a result, 700 million FMs are consumed every day in Africa alone, and this number is 2.2 billion/day in Asia alone, involving large manufacturing and consequent expenditures (Nzediegwu and Cheng et al. 2020; Sangkham 2020; Wu et al. 2020). This has also considerably escalated the volume of FM waste, making waste management rather challenging around the world (Hantoko et al. 2021; Liao

et al. 2021). The main plastic-type material used in surgical FMs is polypropylene which takes many years to disintegrate in traditional waste disposal; on the other hand, when such FM waste ends up in the water bodies, it results in microplastics and breaches our ecosystems by ending up in our sustenance sources (Sarkodie and Owusu 2020; De-la-Torre and Aragaw 2021; Dharmaraj et al. 2021). Thus, viable and productive FM waste management schemes are required, not only from an economic perspective but also to minimize the adverse effect of this pandemic on our ecosystem (Haleem et al. 2020; Ibn-Mohammed et al. 2020; Singh et al. 2020a, b).

Fat clay is a commonly encountered earthen material by civil engineers all over the world, regarded as problematic soil in terms of its mechanical properties (Abbey et al. 2021). The civil engineering structure built over or using such soil remains prone to failure. From an economic point of view, utilization of fat clay with a cost-effective treatment scheme is desirable to limit the use of borrowed material for the construction in the fat clay-rich areas. Different traditional cementitious materials, i.e., cement and lime, are commonly used as ameliorators for the mechanical properties of the fat clay (Eyo and Abbey 2021). However, to promote natural resource conservation and environmental burden reduction, the use of the aforementioned material is needed to be restricted by incorporating possible substitute waste materials (Xu et al. 2020). In this regard, the use of silica fume (SF) in cementitious stabilization of fat clay could be a promising dimension since SF is widely incorporated as a cementitious material in the concrete (Al-Soudany 2018; Phanikumar 2020; Singh et al. 2020a, b). The amelioration of mechanical properties of fat clay with cementitious agents is reliable in terms of strength (Tiwari et al. 2020). However, the ductility of stabilized fat clay with the cementitious additives deteriorates considerably due to increase in the hardened gel in the soil specimen (Phanikumar 2020; Singh et al. 2020a, b). Treatment of fat clay with such additives may not be desirable under seismic loading or where sudden failures are to be avoided. Balanced amelioration of the mechanical properties of fat clay requires not only an increase in strength but the catering of ductility. In literature, different researchers have employed plastic polypropylene fiber (PF) reinforcement to enhance the ductility of the cemented soil since fibers could reinforce the tension cracks under the loading. However, less increase in the strength is observed for the PF as a lone stabilizer as compared to the cementitious stabilizers. Excess use of PFs could also deteriorate the strength characteristics of fat clay (Singh et al. 2020a, b). Balanced amelioration of the mechanical properties of fat clay is achieved by using an amalgamated binary admixture (ABA) having both cementitious agent and PF in few studies (Elkhebu et al. 2019; ur Rehman and Khalid 2021). However, for such ABA, the optimized selection of mix design

of cementitious agent and PFs remains in question because an excessive amount of one could cause adverse impacts (Yilmaz 2015; Elkhebu et al. 2019).

The top and bottom faces of the FM are made of non-woven fabric, while polypropylene is used as its middle layer. Thus, the material of FM urges to reuse its waste as a fiber reinforcement agent in fat clay stabilization. The use of astutely handled FM waste in the construction industry could address the waste management issues of the pandemic in an effective manner. The authors proposed that a balanced amelioration of mechanical properties of fat clay can be achieved by integrating FM fibers and SF in an optimized mix design ratio (ur Rehman and Khalid 2021). Further, to determine an optimized mix design of ABA, the response surface methodology (RSM) is used based on series of experiments in this study. RSM is a strong technique used during the process of production to develop, improve, and optimize product inputs; it involves manifold statistical and mathematical computations. However, this technique is not widely used in soil stabilization as per literature (Güllü and Fedakar, 2017). The current study for the first time employs the RSM to determine the optimized mix design of SF and FM to propose a reasonable FM waste-based ABA for the balanced amelioration of the mechanical characteristics of fat clay. The conclusions offered in terms of optimum stabilizer mix design (FM and SF) ratio are believed to be beneficial for the practitioners and could pave the way for practical usage of FM waste in fat clay stabilization.

Materials and methods

Material characterization

Table 1 manifests the engineering properties of soil selected for amelioration in this study. The liquid limit, plasticity index, and clay content of selected soil were around 83, 52, and 66%, respectively. The soil was classified as fat clay

(CH) as per the Unified Soil Classification System (USCS). The unconfined compressive strength (q_u) and California bearing ratio (CBR) values of the soil were around 153 kPa and 3.1%, respectively. Table 2 presents the chemical analysis results of the soil. The subjected soil contained SiO_2 as the predominant element followed by Al_2O_3 and Cao. Moreover, the ABA used in this study was a mixture of SF and FM. The chemical analysis of SF showed that SF used in this study was predominantly composed of SiO_2 (around 96%) followed by Cao and Na_2O (Table 2). Moreover, FM was used in a shredded form excluding nose strip and ear band materials. Due to COVID-19 restriction, unused FMs were utilized in the current study. However, actual FM waste could be used after proper disinfection. Literature survey reveals different disinfection methods of used FM including prolonged storage, usage of disinfectant solutions, ultraviolet germicidal irradiation, dry heating, and dry microwave heating exposure (Doan 2020; Haghani et al. 2020; Hamzavi et al. 2020; Lowe et al. 2020; Suman et al. 2020; Meyers et al. 2021). Any of these methods could be adopted with intense care; however, their effect on the FM fibers must be taken into consideration before using disinfected FM in soil stabilization. Recommending any disinfection method is beyond the scope of the current study.

RSM description

The following major steps were subsequently performed in RSM: (i) design of experiments, (ii) performance of experiments, (iii) mathematical modeling and statistical evaluation, (iv) optimization of mix design based on required responses, and (v) validation of predicted results of optimized solution based on experimental results. The first two steps define the methodology to acquire a database, and the next steps provide results of response surface analysis (RSA) (Mazumder et al. 2021). In the design of experiments, different mix designs were determined to conduct various tests as

Table 1 Characteristics of selected soil

Characteristics	Selected soil
Liquid limit, w_L (%)	83
Plastic limit, w_p (%)	31
Plasticity index, I_p (%)	52
Clay content (%)	66
Silt content (%)	33
Sand content (%)	11
Maximum dry unit weight, γ_{dmax} (kN/m ³)	15.9
Optimum water content, w_{opt} (%)	24.5
Unconfined compression strength, q_u (kPa)	153.4
CBR-value (%)	3.1
USCS	CH

Table 2 Chemical characteristics of soil and silica fume

Compound name	Soil %	Silica fume %
Calcium oxide (CaO)	8	1.5
Silicon dioxide (SiO_2)	46.8	92
Aluminum oxide (Al_2O_3)	14.6	0.6
Ferric oxide (Fe_2O_3)	6.2	0.5
Magnesium oxide (MgO)	2.8	0.41
Loss of ignition	14.2	3.1
Potassium oxide (K_2O)	-	0.5
Sodium oxide (Na_2O)	-	0.75
Manganese oxide (MnO)	-	0.35
Titanium dioxide (TiO_2)	-	-

per required responses. In the second step, all the designed tests were performed in the laboratory by following obtained design in the former step. In the mathematical modeling step, different models were developed by analyzing the effect of different mix design ratios (SF and FM content) on various responses, i.e., mechanical properties of fat clays. Generally, the quadratic models were developed to compute the responses which were established as of first-, second-, or third-degree polynomials; the general form of the equation is as follows:

$$\hat{Y}(x) = \alpha_0 + \sum \alpha_i x_i + \sum \alpha_{ii} x_i^2 + \sum \alpha_{ij} x_i x_j \quad (1)$$

where $\hat{Y}$ is the predicted response and α and $x_{i,j}$ represent coefficients and i th and j th random variables of a full quadratic model. The coefficients were calculated using numerical regression based on the potential impact of independent variables on the response and their probabilistic distribution. The health of the developed model was checked based on various statistical indicators, i.e., coefficient of determination (R^2), adjusted R^2 ($Adj R^2$), predicted R^2 ($Pred R^2$) adequate precision values, and analysis of variance (ANOVA) analysis describe as follows:

$$R^2 = \frac{SSR}{SSR + SS} \quad (2)$$

$$AdjR^2 = 1 - \frac{n-1}{n-p} (1 - R^2) \quad (3)$$

$$PredR^2 = 1 - \frac{PRESS}{SST} \quad (4)$$

$$AP = \frac{\max(\hat{Y}) - \min(\hat{Y})}{\sqrt{\frac{p\sigma^2}{n}}} \quad (5)$$

where SSR and SS are residual and mean sum of squares, respectively; p and n are model parameters containing intercept and the number of observations, respectively; SST and $PRESS$ are the total sum of square and the prediction error sum of squares, respectively; and σ^2 is the mean square of residual estimated by ANOVA analysis. In addition, prediction accuracy is also measured by comparing the

predicted and actual values of the database (ur Rehman and Zhang 2021). Similarly, the normality control and equal variance assumption were conducted by comparing the residue to the predicted response variables. Afterward, optimized mix design was determined by engaging mathematical models established in step iii in an algorithm to determine the desirability function. Finally, the responses of optimized mix design determined in step iv were validated against actual test results.

Design of experiment

The face-centered central composite design (FCCCD) approach was employed in the current study, to design the experimental scheme. Initially, the boundary conditions were defined for the experimental scheme with two variables having different maximum and similar minimum values (Table 3). Fourteen experiments were designed with 6 central points and 8 axial points using FCCCD constraints. In the center points, the curvature of the built-in function of responses with independent variables was defined. The addition of axial points allowed the effective estimation of pure quadratic terms of available curvature (Güllü and Fedakar, 2017). Two additional axial points were also incorporated to enhance the database making the total sets of experiments to be 16. In addition, four responses were selected for the evaluation, i.e., q_u and CBR value, brittleness index (I_B), and deformability index (I_D), wherein q_u and CBR values were used to evaluate strength properties of the soil and I_B and I_D were used to evaluate the ductility of the soil (Table 4).

Sample preparation and testing Considering the designed experimental scheme, different tests were conducted including unconfined compression tests and CBR tests. Standard compaction tests were also conducted to determine the optimum water content (w_{opt}) and maximum dry density (γ_d) of soil samples, since samples for the response measuring tests were prepared at the standard w_{opt} and γ_d (Shehzad et al. 2015; Khalid and Rehman 2018). Shredded FM and SF were diligently mixed using a soil mixer to circumvent the fiber breakage and segregation in the soil-additive matrix. A strain-controlled axial load was applied to the sample at a rate of 1.0 ± 0.1 mm/min during the unconfined compression test according to ASTM D2166. The axial strain was

Table 3 Boundary condition of factors in RSM

Variables				Levels					
Name	Code	Units	Subtype	Minimum	Maximum	Coded values		Mean	Std. dev
SF	A	%	Continuous	0	16	−1.00=0.00	1.00=16.00	0.00=8.5	5.26
FM	B	%	Continuous	0	1.2	−1.00=0.00	1.00=1.20	0.00=0.6375	0.38

Table 4 Face-centered central composite design experiments and test results

Run	SF (%)	FM (%)	q_u (kPa)	I_B	I_D	CBR (%)
1	0	0.6	280.1	0.05	0.96	5.6
2	8	0.6	2121	0.71	0.91	43.1
3	8	0.6	2121	0.71	0.91	43.1
4	16	0.6	2993	1.24	0.72	61.3
5	8	0.6	2121	0.71	0.91	43.1
6	16	1.2	3378	1.20	0.77	70.2
7	8	0.6	2121	0.71	0.91	43.1
8	8	0.0	1730	1.04	0.65	36.0
9	0	0.0	153.4	0.00	1.00	3.1
10	8	0.6	2121	0.71	0.91	43.1
11	8	0.6	2121	0.71	0.91	43.1
12	8	1.2	2389	0.46	0.99	49.4
13	0	1.2	325.1	0.09	0.98	6.5
14	16	0.0	2800	1.52	0.54	64.0
^a 15	8	0.9	2500	0.56	0.98	52.0
^a 16	16	0.9	3077	1.19	0.74	64.0

^aAdditional tests

applied in a manner that both q_u and residual strength (q_r) (if exist) could be measured (Rehman and Zhang, 2019, Rehman et al., 2020, Rehman and Zhang, 2021). The I_B and I_D were computed by determining q_u , q_r , and strain at failure (ε_f) for treated and untreated soils using the following equations:

$$I_B = \frac{q_u}{q_r} - 1 \quad (6)$$

$$I_D = \frac{\varepsilon_{f(\text{treated})}}{\varepsilon_{f(\text{untreated})}} \quad (7)$$

In addition, un-soaked CBR tests were carried out by following ASTM D1883-14, to examine the strength characteristics of the soil for use in subgrade construction. It is important to mention that 14-day curing is selected in the current study as by a trial study it was observed that ABA-treated soil gained substantial q_u after 14 days of curing and the marginal increase occurred beyond this curing time (ur Rehman and Khalid 2021). Thus, to avoid large delays and complexity, 14-day curing of sample for the main study was adopted, and it was done by wrapping samples in a polythene cling sheet and placing them in a desiccation jar.

Results and discussions

Mathematical modeling

ABA mix design effect on q_u The effect of different mix designs of SF and FM on the q_u was evaluated, and three-

dimensional (3D) surface response and contour plots are plotted for the best-fit mathematical model in Fig. 1. It was observed that q_u increased with the increase in the SF and FM in the mix design; a large increase was observed for the increase in the former as compared to latter. Moreover, with an increase in the FM content in the ABA, the q_u of treated soil increased to a certain limit and showed a slight decrease (Fig. 1a). A complete quadratic model, without transformation, was evaluated and then modified with back-calculation analysis to keep $p < 0.05$ for all intercepts. The following mathematical model is derived to define q_u using the input variables, i.e., SF and FM, by keeping λ value equals to unity:

$$q_u = 2122.06 + 1380.3A + 538.52B + 85.25A \cdot B - 488.74A^2 - 0.33B^2 - 191.15A^2 \cdot B - 176.32B^3 \quad (8)$$

where A and B are SF and FM, respectively. Figure 1b shows the contour plot of this response surface. A good agreement between the actual and predicted values of q_u was observed around 45° line (Fig. 1c), showing the significance of Eq. 8. The normal probability plot of the RSM model for q_u is constructed in Fig. 1d. It can be seen (Fig. 1d) that for this model, against normal probability, the internally studentized residuals were tracked around a straight line, which means that the normal assumption was met. In addition, the perturbation plot is presented in Fig. 1e, for a better understanding of the effect of SF and FM contents on the q_u of ABA-treated soils at a particular point. A steep slope was observed with an increasing trend for both SF and FM, which means that the q_u increased with an increase in SF and FM; however, a more steep line and a larger increase in the q_u was observed with an

Fig. 1 RSM-based analysis of q_u : **a** 3D response surface, **b** contour plot, **c** predicted versus actual value, **d** normal probability plot, and **e** perturbation plot

increase in the SF, which means that SF is a more sensitive parameter for the q_u of ABA-treated soil. These analyses depict the importance of the presence of SF in the FM-based ABA in ameliorating the strength of a fat clay.

ABA mix design effect on I_B Figure 2 presents the effect of SF and FM contents in an ABA on the I_B of the treated soil, which is an inverse representation of the ductility of the soil. It was observed that I_B increased as the SF content was increased; conversely, I_B decreased as the FM was increased in the ABA. However, when FM was added in the absence of SF, the I_B almost remained unchanged. A 3D response surface was observed to capture the effect of mix design on I_B , which can be quantified by the following mathematical model (Fig. 2a); the contour plot of this surface is shown in Fig. 2b.

$$I_B = 0.7 + 0.63A - 0.14B - 0.1A \cdot B \quad (9)$$

A good agreement along the 45° line was observed between actual and predicted I_B values using Eq. 8 (Fig. 2c). In addition, in the normal distribution plot (Fig. 2d), the data points coincided with the normal line showing that data was normally distributed. Moreover, the perturbation plots showed that the increase in the SF and FM improved and deteriorated the I_B value, respectively, in a sensitive manner (Fig. 2e). However, deterioration caused by SF was observed to be slightly larger than the improvement imparted by the FM. This shows that the deterioration caused by the SF can be well ameliorated by the FM. This is in line with past literature on fiber and cementitious improvement of soil (Tiwari et al. 2020; Elkhebu et al., 2019; Abdi et al. 2021). This shows that FM can do damage control in terms of deterioration of ductility imparted by the SF while generating cementation in ABA-treated soil. FM acts as a reinforcing agent in the cemented soil matrix, which is responsible for high strength, to ensure that the ductility of treated soil does not vanish. This proves that assimilated SF and FM can ensure balanced mechanical characteristics of treated soil as postulated. On the other hand, the aforementioned analysis also shows that for maximum balanced amelioration of strength and ductility, optimum mix design should be adopted.

ABA mix design effect on I_D The effect of the mix design of ABA was also assessed on I_D , as shown in Fig. 3. The trend of the effect of SF and FM content on the I_D was observed to be almost similar to that on I_B . The following quadratic model with no transformation ($\lambda = 1$) was obtained to define the 3D surface response of the I_D using SF and FM as the predictors (Fig. 3a).

$$I_D = 0.91 - 0.16A + 0.093B + 0.059A \cdot B - 0.047A^2 - 0.052B^2 \quad (10)$$

The contour plot of this 3D surface response is shown in Fig. 3b. For this model, a reasonably less scatteredness

of the actual and predicted value of I_D was observed along the 45° line (Fig. 3c). The data was normally distributed as verified by the distribution of internally studentized residuals along a straight line against normal probability (Fig. 3d). The perturbation plot shows that SF and FM were almost equally sensitive parameters in terms of I_D , wherein the former posed a negative impact and latter posed a positive impact on I_D (Fig. 3e). Thus, deterioration of deformability caused by SF can be controlled by FM content in the ABA, proving the importance of integrating SF and FM to prepare a balanced cementing admixture for fat clay.

ABA mix design effect on CBR-value CBR-value was observed to increase with the addition of both SF and FM; however, generally, a slight downward curvature was observed as the FM content increased to its maximum value set in this study (Fig. 4). Consequently, a 3D response surface was observed to capture the effect of SF and FM on the CBR-value of treated soil bounded with the following mathematical model (Fig. 4a).

$$CBR = 42.18 + 26.33A + 12.27B + 0.007A \cdot B - 8.78A^2 + 0.75B^2 - 5.42A^2 \cdot B + 3.76A \cdot B^2 - 5.14B^3 \quad (11)$$

The contour plot of this response surface is presented in Fig. 4b. A marginal deviation among actual and predicted values was observed for this model with a normal data distribution (Fig. 4c-d), showing the statistical reliability of this model. The perturbation plot shows that both SF and FM contributed to the CBR-value; however, SF is a more sensitive variable (Fig. 4e). It is important to note that CBR-value is an important indicator to determine the suitability of soil for subgrade construction of roads and highways. These results show that the potential of a native fat clay to be used in the subgrade construction can be enhanced by stabilizing it using the appropriate mix of ABA.

Statistical analysis of ABA mix design models

For further evaluation of developed models in the current study, various important statistical model validation parameters are presented in Table 5. A high value of R^2 , $Adj R^2$, and $Pred R^2$ for all the developed models in the current study indicates the good health of these models. The difference between all these parameters was observed to be less than 0.2 which indicates that these parameters are rationally in the agreement. A high value of adequate precision factor (adequate precision > 4) was observed for all the developed models; this indicates that these models can reliably be used to predict the corresponding responses. The ANOVA results for a full regression model are also presented in Table 5, a high F value ($F > 3.9$) was observed for all models, and very

Fig. 2 RSM-based analysis of I_B : **a** 3D response surface, **b** contour plot, **c** predicted versus actual value, **d** normal probability plot, and **e** perturbation plot

Fig. 3 RSM-based analysis of I_D : **a** 3D response surface, **b** contour plot, **c** predicted versus actual value, **d** normal probability plot, and **e** perturbation plot

Fig. 4 RSM-based analysis of CBR: **a** 3D response surface, **b** contour plot, **c** predicted versus actual value, **d** normal probability plot, and **e** perturbation plot

Table 5 Model validation for responses and ANOVA results for full regression model

Source	R^2	$Adj R^2$	$Pred R^2$	Adeq preci- sion	Std. dev	Mean	Sum of squares	Mean square	F value	Prob > F	ANOVA remarks
Equation 8	0.99	0.99	0.94	50.9	86.10	2021.9	1.4E7	2E6	276.962	< 0.0001	Significant
Equation 9	0.96	0.95	0.86	34.97	0.08	0.725	2.82	0.94	119.736	< 0.0001	Significant
Equation 10	0.899	0.849	0.71	15.9	0.05	0.86	0.25	0.05	17.920	< 0.0001	Significant
Equation 11	0.99	0.99	0.81	47.9	1.77	40.86	5.9E3	7.5E2	238.785	< 0.0001	Significant

insignificant values of probability ($p < 0.05$) were observed. These results show that all the models developed in the current study are having good statistical health.

Optimization of ABA mix design In order to establish the optimum quantities for the independent variables (SF and FM) in the ABA for maximum performance considering strength behavior in terms of q_u and CBR-value and ductility behavior in terms of I_B and I_D , an optimization study was carried out in this paper using the approach to compute the individual desirability functions (d_i) outlined for each subjected dependent (response) variable as follows:

$$d_i(\hat{Y}_i) = \begin{cases} 0 & \text{if } \hat{Y}_i(x) < \text{Max}_i \\ \left(\frac{\hat{Y}_i(x) - \text{Max}_i}{\text{Max}_i - T_i} \right)^s & \text{if } T_i \geq \hat{Y}_i(x) \geq \text{Max}_i \\ \left(\frac{\hat{Y}_i(x) - \text{Min}_i}{\text{Max}_i - T_i} \right)^t & \text{if } \text{Min}_i \geq \hat{Y}_i(x) \geq T_i \\ 0 & \text{if } \hat{Y}_i(x) > \text{Min}_i \end{cases} \quad (12)$$

where Min_i and Max_i are the minimization and maximization values, respectively, and T_i is the target value, and s and t render the strictness level of the d_i function for maximization and minimization goals. Global desirability (D) based on d_i is computed using the following equation (Ferdosian and Camões 2017; Pinheiro et al. 2020):

$$D = (d_1^{r_1} \cdot d_2^{r_2} \cdot d_3^{r_3} \cdot \dots \cdot d_n^{r_n})^{\frac{1}{\sum r_i}} = \left(\int_{i=1}^n d_i^{r_i} \right)^{\frac{1}{\sum r_i}} \quad (13)$$

where n is the number of responses and r_i is the sensitivity factor for each response, which is increasingly rated from 1 to 5. The overall desirability was taken as the arithmetic mean of all individual desirability for which 0 and 1 indicate the least and highest threshold values. It is important to mention that in this study, to outline the strength behavior of treated soil, q_u and CBR-value were selected so that optimized solution could be accepted for a wide range of applications, i.e., buildings, roads and highways. In this study, a maximization goal was adopted for q_u , CBR-value, and I_D , and a minimization goal was selected for the I_B (Fig. 5a). Moreover, the maximum CBR-value was limited at 50% as this indicates a momentous value. For all these goals, a significant D -value close to 1 was obtained for a mix design having 7.9% SF and 1.2% FM (Fig. 5b). This indicates that with this mix design, the best possible balanced amelioration of the mechanical properties considering strength and ductility could be achieved. It can be observed that increasing SF beyond the achieved optimized mix design value decreases desirability. Moreover, this mix design may change as goals are changed; for instance, by ignoring CBR-value in optimization and keeping goals for remaining responses to be the

Fig. 5 Optimization of mix design: **a** goal setting and **b** desirability analysis

same, the optimized mix design was obtained at 6.2% of SF and 1.2% FM with almost similar D -value. These analyses show that change in the mix design of ABA has a significant impact on the mechanical performance of the ABA-treated soil. Thus, to achieve balanced mechanical amelioration of fat clay, optimized mix design of ABA should be used in the field.

Validation of ABA mix design

The final step in RSM is the validation of the developed models. For this purpose, an experimental program was conducted for the optimized mix design obtained in the current study. Thus, by mixing 7.9% and 1.2%, an ABA was prepared and mixed with soil to prepare a sample for the unconfined compression and CBR tests. Table 6 presents the comparison of predicted responses and actual test results for the optimized mix design; it was observed that the developed models can reasonably predict different responses with a fringe error (maximum error $\leq 8\%$). The stress–strain curve

obtained from the unconfined compression test is also presented in Fig. 6a, and it can be observed that high strength and reasonable ductility were achieved with the optimized mix design of the current study. In addition, the ductility was observed to be mainly catered by the fiber bridging effect imparted by FM fibers in the tension cracks as can be seen in open tension cracks of the ABA-treated sample after failure (Fig. 6b).

Cleaning aspects

Cleaner production and pollution reduction measures by productive waste reuse can benefit both the economy and the environment. In this study, two waste by-products are mixed to prepare an ABA as a replacement of conventional fat clay stabilizers, i.e., cement. In addition, the appropriate mix design of ABA as determined in the current study presents balanced amelioration of the fat clays in terms of strength and ductility characteristics, unlike the conventional stabilizing materials which only ameliorate strength

Table 6 Response results of the experiment and prediction model for optimal mix design

Response	SF (%)	FM (%)	q_u (kPa)	I_B	I_D	CBR (%)	Desirability
Predicted	7.9	1.2	2481.2	0.50	0.95	50.0	0.88
Experimental	7.9	1.2	2380.0	0.45	0.97	49.0	
Error (%)	-	-	3.7	8.0	4.5	2.0	

Fig. 6 Validation of optimized mix design: **a** unconfined compression test result and **b** fiber bridging

characteristics of the soil. Thus, ABA could help in mitigation of environmental and natural resource consumption issues caused by the production of conventional stabilizing material and cleaning of different emerging wastes, i.e., FM waste and SF through more efficient soil stabilization than conventional materials.

As per the modified Nzediegwu and Chang (2020) model, the FM waste is estimated to be around 11,308 Mg/day in Asia alone which is an emerging problem threatening to pose severe long- and short-term environmental issues, e.g., disposal and burning of non-renewable and non-biodegradable FM waste material release microplastics and CO₂ to the ecosystem, respectively (Sangkham 2020). The actual production of SF is still unknown, and this production is ever increasing due to industrialization; however, roughly the estimated production of SF waste is around 5480 Mg/day globally (Türköz et al. 2018). Environmentalists are concerned about the correct disposal of SF as an industrial waste since it can create serious health problems if it is directly released into the ecosystem. To estimate the magnitude of waste by-products that could be incorporated in a geotechnical application through the current soil stabilization scheme, the mass of stabilizing material, M_{st} , required for the soil stabilization in any project is computed using the following equation:

$$M_{st} = \frac{\gamma_s v_s \Delta_{st}}{100} \quad (14)$$

where γ_s and v_s are the specified dry density and volume of the soil and Δ_{st} is the percentage by weight of stabilizing material. For instance, using an optimized ABA mix design for a 1 km two-lane road, to stabilize 0.25 m thick and 18.5 kN/m³ of subgrade soil, 43 Mg and 281 Mg of FM and SF waste could be utilized, respectively. Thus, the proposed optimized ABA has a vast potential of productively managing FM and SF wastes. In addition, the

required amount of cement (for $\Delta_{st} = 10\%$) to stabilize soil with similar specifications as mentioned above could be around 356 Mg. Thus, using the proposed optimized ABA for a 1 km two-lane road project in place of cement as a fat clay stabilizer could avoid carbon dioxide emission of around 79,032 kg of C and can also save 42,720 kWh and 1174.8 GJ of electrical and thermal energy, respectively, by restricting cement manufacturing (Sousa and Bogas, 2021). The determined ABA in this study has the potential to promote the pragmatic reuse of the FM waste in soil stabilization. This can help to resolve the FM waste disposal and pertinent environmental problems, mechanical vulnerabilities of fat clays, and natural construction material consumption-related issues. Thus, the utilization of optimized ABA holds promising environmental and economic benefits.

Cleaner production encompasses many operational practicalities of safe health/environmental practice including safe logistics of waste collection and making it ready for the final application. Reutilization of SF in the construction industry is well known, and safe protocols to collect it from the parent industry and making it ready for application in the construction industry are well in practice. In contrast, the use of FM waste in construction is not well established, and due to large health risks involved with this waste, astute protocols of FM waste handling and disinfection are needed to be established and followed. FM waste is needed to be handled as hazardous waste, and thus, care must be taken from collecting it from the primary consumer level to the proposed geotechnical application. The proposed cleaner production process of FM waste involves the collection, transportation, disinfection shredding, and final geotechnical application as shown in Fig. 7. Carefulness must be maintained in all the involved steps (Fig. 7). For instance, during transportation, tarps or other dust-proofing materials should be used to cover delivery trucks, and less human interference should be involved in the handling of FM waste (Saberian et al.

Fig. 7 Proposed procedure of FM waste management for fat clay stabilization (arrows in black indicate that delay is desirable for preceding activity)

2021). To restrict COVID-19 exposure at these stages, it is suggested to perform proper disinfection involving less human interference, by prolonged storage (not shorter 72 h), chemical disinfectant, exposure of FM waste to sun and air (for more than 72 h), or their combinations (Doan 2020; Haghani et al. 2020; Hamzavi et al. 2020; Lowe et al. 2020; Meyers et al. 2021; Suman et al. 2020). Moreover for the geotechnical application of FM waste, during shredding of FM and application to the soil, automated machinery should be involved as much as possible. Any worker involved in handling and application of FM waste in construction must be protected with PPE and regularly undergo health monitoring. The machinery, trucks, and logistics involved from collection to the geotechnical application of FM waste must be regularly disinfected.

Conclusions

In this study, a novel admixture prepared by blending SF and shredded FM is evaluated for the balanced treatment of mechanical properties of fat clay. For this purpose, RSM is applied and different mathematical models are developed to predict different responses, and the optimized mix designs are proposed considering the possible maximum performance of ABA to improve strength and cater brittleness of treated soil. The following are the findings of the current study:

- SF and FM contributed to the amelioration of strength characteristics, i.e., q_u and CBR -value of the ABA-treated soil; however, the latter played a marginal role in comparison to the former. In addition, a slight curvature in the 3D response surface of strength characteristics of treated soil was observed beyond the central point towards increasing FM content showing that excessive use of FM in combination with SF may slightly deteriorate strength. On the other hand, SF content was observed

to be a sensitive input of ABA in deteriorating the ductility of treated soil as indicated by the increase in I_b and decrease in I_D . Conversely, FM content in ABA ameliorated the deteriorated ductility by SF. However, the deterioration impact of SF on ductility was slightly higher than the converse impact of FM. This shows that FM acts as a reinforcing agent in the cemented soil matrix, which is responsible for the attainment of high strength, to ensure that ABA-treated soil does not lose much ductility. However, 3D RSA emphasized that for maximum balanced amelioration of strength and ductility, optimum mix design should be determined.

- The mathematical models were developed in the current study to predict q_u , I_b , I_D , and CBR -value of ABA-treated soil for different mix designs of ABA. These models were observed to have high values of R^2 , $Adj R^2$, and $Pred R^2$ with a difference among these parameters less than 0.2. In addition, an insignificant p -value < 0.0001 was observed for all models; thus, these models were statistically valid.
- For multiple applications, i.e., roads and buildings, the desired maximization of q_u , CBR -value, and I_D and minimization of I_b of treated soil were achieved by a singular mix design of ABA having 7.9% SF and 1.2% FM with a high D -value close to 1. In addition, by ignoring CBR -value in optimization and keeping goals for remaining responses to be the same, the optimized mix design was obtained at 6.2% of SF and 1.2% FM with almost similar D -value. Thus, these application-based optimized ABA could be adopted in the field for maximum balanced amelioration of fat clay.
- The analysis of the cleaning aspect of this study showed that the use of optimized ABA in place of cement for sub-grade improvement of 1 km two-lane road could avoid CO_2 emission of around 79,032 kg of C, save 42,720 kWh and 1174.8 GJ of electrical and thermal energy, respectively, and clean 43 Mg and 281 Mg of FM and SF

wastes, respectively. Thus, the current COVID-19-related and existing environmental problems could be minimized through this solution. However, proper protocols for disinfection and handling of the FM waste are required to be established and strictly followed before using it in soil stabilization.

It is important to mention here that the current study provided this geotechnical solution to reuse FM waste in fat clay stabilization by using unused FM due to COVID-19 restrictions; however, actual FM waste should be used after proper disinfection. The disinfection method of FM waste and its impact on soil stabilization potential were not included in the scope of the current study; carefully designed studies could be conducted for that purpose in the future.

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Author contribution ZR: Conceptualization, methodology, validation, investigation, writing original draft, formal analysis, and visualization. UK: Investigation, data curation, resources, validation, writing–review and editing, and visualization.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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